CHAPTER 9
THE REMNANTS OF STARS

9.1 Introduction

In this chapter we look at what remains of a star after nuclear burning processes cease. We shall use the term 'stellar remnants' to describe these objects, which essentially form from the dead cores of stars. (This is distinct from the term 'supernova remnant' that refers to the envelope that is ejected following a supernova explosion.) These stellar remnants are some of the most bizarre objects in the Universe: white dwarfs, neutron stars and black holes. Their common features are small radii, extremely high densities and intense gravitational fields. We shall see that the type of remnant that is left at the end of a star's life depends on its initial mass; that white dwarfs are the end point of evolution of low-mass stars, while neutron stars and black holes arise from the catastrophic events that mark the end of the life of a high-mass star.

Because of their small radii, isolated stellar remnants tend to have very low luminosities and hence are difficult to detect. This is exemplified by the case of black holes; they are effectively black, and it has been a major challenge to astronomers to prove their existence. As we will see, the key to solving this problem lies in the observation of interacting binaries, which can be considered to be laboratories for studying not just black holes, but all kinds of stellar remnant.

9.2 White dwarfs

We saw in Chapter 8 that stars with an initial mass of less than about $11M_{\odot}$ will shed a planetary nebula as they reach the final stages of their lives. It is as this phase of stellar evolution comes to an end that white dwarfs are formed. The class of stars that are called white dwarfs were introduced in Section 4.2.2 on the basis of their observational properties.

- ■ What properties of white dwarfs can you recall?
- ❑ They are very small (Earth-sized), have low luminosity and have surface temperatures typically in the range 5000 to 25 000 K.

Why should we connect these objects with the late stages of stellar evolution? One clue comes from looking at the central stars of planetary nebulae on the H–R diagram. These are shown in Figure 9.1, together with the positions of typical white dwarfs. If we assume that the star at the centre of a planetary nebula is the hot core of a giant that is running out of nuclear fuel, and that the only course left open to it is to cool and contract under gravity, then we can predict that it would evolve along the track shown, ending in the region of the white dwarfs. This is the type of evolutionary picture that is generally accepted today. Let's assume that this is broadly speaking correct, and take a closer look at some properties of white dwarfs.

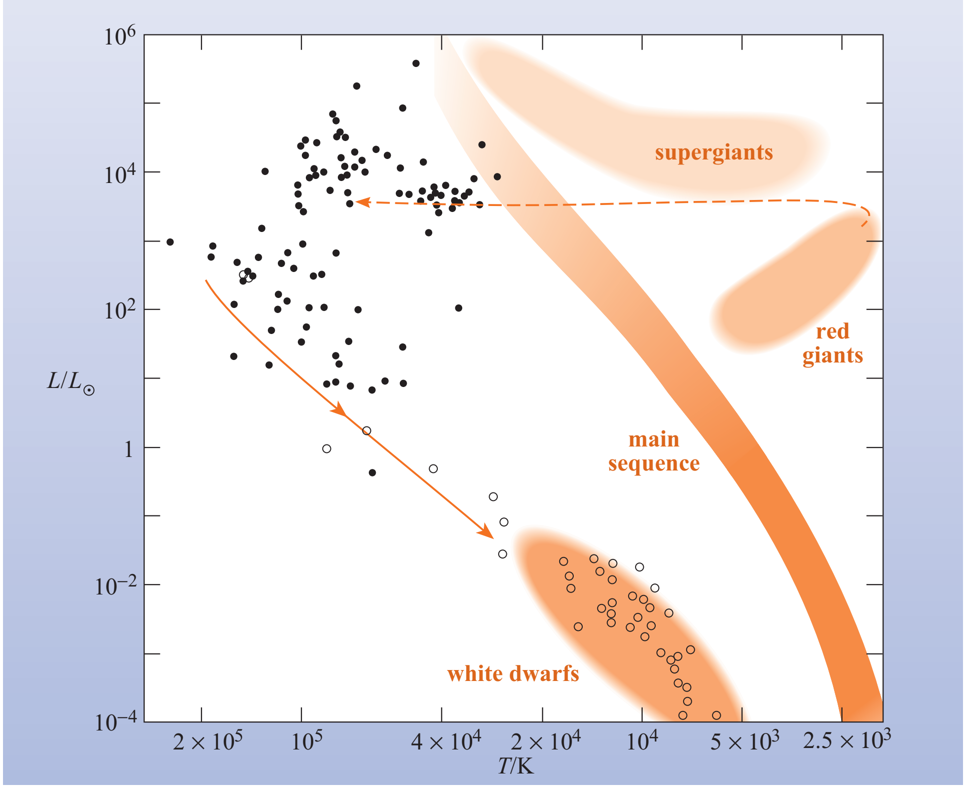


Figure 9.1 The positions of central stars associated with planetary nebulae (dots) and of white dwarfs (open circles) on the H–R diagram. Also shown (solid line) is the evolutionary track that would be followed by a star of constant radius as it cools and (dashed line) a schematic evolutionary track between the regions occupied by AGB stars (Section 8.2.1) and by the central stars of planetary nebulae.

The core of a white dwarf consists of electron degenerate material. With no possibility of initiating any further nuclear reactions, the remnant of the giant, possibly devoid of its outer layers through a combination of the copious stellar wind in the AGB phase and the ejection of a planetary nebula, contracts under the force of gravity. The density in the core shoots up until electron degenerate conditions are created. This assertion is supported by reference to Figure 7.4. The density and temperature conditions believed to pertain in the cores of white dwarfs are shown – they are clearly in the area where material is electron degenerate.

Such material gives rise to a degeneracy pressure (in this case electron degeneracy pressure – see Section 7.2.4) and this plays a vital role in counteracting the collapse of the core of the dying red giant. The pressure gradient due to degeneracy pressure within the core halts any further contraction and forms a stable star – a white dwarf. However, this halted contraction doesn't prevent a typical white dwarf from having some fairly exotic properties.

QUESTION 9.1

Assuming that a typical white dwarf has a radius of 7×10^3 km and a mass of $0.6M_\odot$, calculate its average density. How does this compare with the value for the Sun?

In principle, the equations of stellar structure can be solved for a white dwarf just as for a main sequence star.

- What are the main differences in the data used for solving the equations of stellar structure for a white dwarf, as opposed to a main sequence star?
- The major differences are in the size and the composition.

What emerges from solving these equations for a typical white dwarf? First, it is found that for a surface temperature of about 10^4 K, the core temperature will be in the region of 10^7 K. At first sight this might appear anomalous, as we have already seen that a temperature of this order is able to trigger nuclear fusion reactions in a star like the Sun.

- Given its likely composition, why shouldn't such fusion reactions also occur in a white dwarf?
- A white dwarf, being essentially the collapsed core of a giant, is likely to be almost devoid of hydrogen, much of it having been used during the main sequence lifetime or thrown off into the interstellar medium in the form of a planetary nebula. The white dwarf, depending on the mass of its 'progenitor' or parent, is likely to consist largely of helium, or carbon and oxygen, or heavier nuclei. Such nuclei require higher temperatures before fusion reactions can occur.

Solution of the relevant equations does show, not surprisingly, that the outer layers of a white dwarf are not degenerate and must therefore be treated with different equations for certain properties. Perhaps more surprising is the prediction that as the mass increases, the radius decreases. Following from this is the prediction of an upper limit to the mass of a white dwarf, above which electron degeneracy pressure can't halt the contraction. This value is about $1.4M_\odot$ and it is known as the **Chandrasekhar limit** after the Indian astrophysicist who predicted it. How does this rather surprising prediction compare with observations? Actually quite well – no white dwarfs have been found above this mass limit.

SUBRAHMANYAN CHANDRASEKHAR (1910–1995)

Subrahmanyan Chandrasekhar (Figure 9.2) was brought up in India. While he was travelling by boat from India to England on his way to Cambridge in 1930 he worked out that there would be a maximum mass that a white dwarf could have. In 1936 he moved to the University of Chicago, where he spent the rest of his working life, and was notable for the mathematical detail with which he explored astrophysical topics. In 1983 he was awarded the Nobel prize, and in 1999 a major NASA X-ray observatory was named Chandra in his honour.

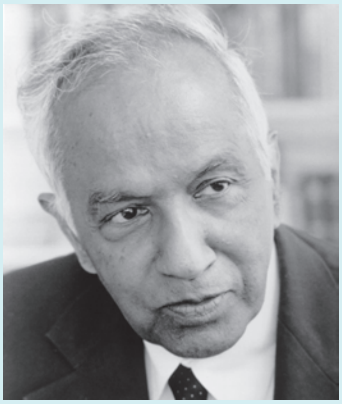


Figure 9.2 Subrahmanyan Chandrasekhar. (University of Chicago)

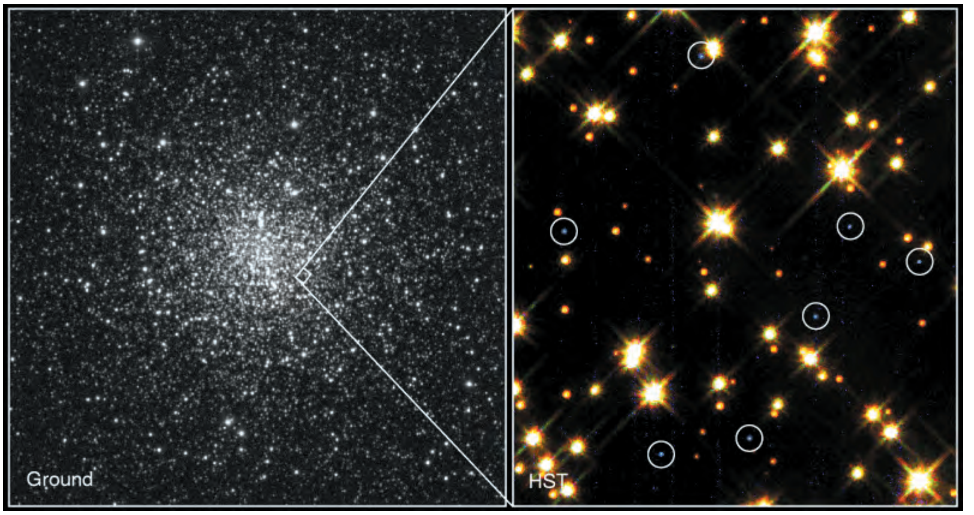


Figure 9.3 The results of a search for white dwarf stars in the globular cluster M4. The globular cluster is at a distance of about 2 kpc from the Sun and contains more than 10^5 stars. The left-hand image shows the entire cluster as viewed from a ground-based telescope; the area of the detailed search made using the Hubble Space Telescope is indicated. The right-hand image shows the seven isolated white dwarf stars (circled) that were found. The other stars in the image are main sequence stars and red giants. ((left) M. Bolte (University of California, Santa Cruz); (right) H. Richer (University of British Columbia)/NASA)

What about the frequency of occurrence of these objects? Here we run into the problem of selection effects. Because white dwarfs are rather faint, we probably are not able to observe many of them. When we take account of this fact, it appears that white dwarfs are really rather common, perhaps constituting 10% of all stars in our Galaxy. As an illustration of the ubiquity of white dwarfs, Figure 9.3 shows the results of a sensitive survey of stars in the globular cluster Messier 4 (M4) made with the Hubble Space Telescope: the right-hand panel shows seven isolated white dwarfs (circled) that were discovered within the survey area.

What about stars with intermediate mass, above the Chandrasekhar limit of $1.4M_\odot$ and below about $11M_\odot$? Remember the prediction that white dwarfs cannot have a mass above $1.4M_\odot$. Therefore, if these intermediate mass stars are to become white dwarfs, as seems to be the case, they must lose mass. The shedding of mass, as we have seen, plays a significant part in these later stages of stellar evolution, through stellar winds and planetary nebulae. However, from what we know of them, it doesn't seem that these mechanisms are able to remove enough mass to bring the more massive stars below the Chandrasekhar limit. So some difficulties still remain to be explained in this picture of the final stages of evolution of intermediate mass stars.

QUESTION 9.2

If the luminosity of a white dwarf drops by a factor of 10^4, and its radius stays constant (a feature of degenerate matter), what has happened to its surface temperature? (Answer this question from theory, and check your answer by referring to Figure 9.1.)

Is there any future for a star after the white dwarf phase? With the exception of cases where a white dwarf exists in a close binary system (Section 9.5) the answer is almost certainly 'no'. The fate of the isolated white dwarf is to cool and fade. The white dwarf has a small surface area, and hence its luminosity is relatively low. This means that the thermal energy of the white dwarf is lost slowly: it cools on a timescale of 10^9 years or more. As the white dwarf cools, it follows a track on the H–R diagram similar to that shown in Figure 9.1 and moves to the lower right. This is generally regarded as a final resting point in stellar evolution, and its material is now essentially lost from taking any further part in the cosmic cycle. This is to be the final fate of our Sun – a dark, cold, dense sphere of degenerate material, rich in carbon and oxygen and only about the size of the Earth!

9.3 Neutron stars

What is left after a Type II supernova explosion? We saw in Chapter 8 that the explosion ejects the outer layers of the star into space, and leads to the formation of a supernova remnant. Here we will consider what is left of the core of the star that underwent the explosion. (Note that the term *supernova remnant* is used by some authors to include any central object; here the term refers only to the material that is ejected.)

In earlier sections we followed the evolution of the core of the star as it collapsed rapidly. The implosion had been triggered by the photodisintegration of the iron group nuclei in the core, and the reaction

$$e^- + p \rightarrow n + \nu_e$$

which absorbed electrons (removing their contribution to the pressure supporting the star) and produced neutrinos (which carried away energy). You saw that, even if the core mass exceeds the Chandrasekhar limit of $1.4M_\odot$, the collapse could be brought to a sudden halt when the density became comparable with the density of an atomic nucleus, and a new form of degeneracy pressure due to the neutrons came into play.

Neutron degeneracy pressure is the same phenomenon as the electron degeneracy pressure that you met in connection with the cores of red giants (Section 7.2.4) and with white dwarfs (Section 9.2), except that the particles providing the pressure in this case are neutrons, and the density is much higher. The existence of this pressure allows the presence of another stable form of matter, more dense than that of the white dwarf star, in which the strong forces of gravitational contraction are balanced by the pressure from the neutrons.

We saw earlier that the Chandrasekhar limit is the maximum mass that can be supported by the electron degeneracy pressure. Similarly for neutrons there is a limit, but because the composition of the star is different, the limit is different. There is some uncertainty over exactly what the limit is since the extreme environment of the inside of a neutron star is not fully understood. The limit is estimated to be between $3M_\odot$ and $5M_\odot$ and most astrophysicists suspect that the true value lies close to $3M_\odot$. Despite the uncertainty over the physics of neutron stars, it is well established that no star could be supported against gravity by neutron degeneracy pressure if its mass exceeded $5M_\odot$.

■ Suppose the mass of the collapsing core is bigger than this limit, what happens?

❏ The collapse of the imploding core of the supergiant is not halted and it continues to shrink under gravity to even greater densities.

What it becomes, we shall see in the next section. In this section we shall concentrate on cores where the mass is less than $3M_\odot$. So, after the collapse, what do we have? Something small, dense and very rich in neutrons! This is a neutron star, a body of up to a few solar masses, packed into a sphere about 10 km in radius.

QUESTION 9.3

Calculate the average density of a $1.5M_\odot$ neutron star of radius 10 km. How many tonnes would a thimble-full contain? (Take the volume of a thimble to be 1 cm^3. Also note that 1 tonne = 1000 kg.)

These densities are hard to envisage, and hard to believe! Something comparable would be achieved if Mont Blanc were compressed to thimble size, or if the whole Earth shrunk to a few hundred metres across.

The gravitational field at the surface of the neutron star is correspondingly enormous.

QUESTION 9.4

The acceleration due to gravity (g) at the surface of a spherical body of mass M_* and radius R_* is given by,

$$g = \frac{GM_*}{R_*^2}$$

Calculate the acceleration due to gravity at the surface of:

(a) The Earth (mass = 5.98×10^{24} kg, radius = 6378 km).

(b) A neutron star of mass $1.5M_\odot$ and radius 10 km.

QUESTION 9.5

Use your answers from Question 9.4 to calculate the speed of an object at a time of 1.0×10^{-5} s after it is dropped from rest from a position just above the surface of:

(a) The Earth.

(b) A neutron star of mass $1.5M_\odot$ and radius 10 km.

(Assume that the object is dropped from such a height that it does not hit the surface during that time, and that the acceleration due to gravity can be assumed to be constant throughout the motion.)

So neutron stars are small objects, rich in neutrons, with very high densities and huge surface gravitational fields. You may, justifiably, feel that this is already plenty of unusual properties for any type of astronomical object, but the bizarre nature of these objects does not end here. The next property we shall consider is the rotation of the star, but first it is necessary to introduce the concept of angular momentum (see Box 9.1).

BOX 9.1 CONSERVATION OF ANGULAR MOMENTUM

If you have ever watched a high diver you may have noticed that, when tight-tucked, the diver somersaults rapidly during the dive, but when stretched out tumbles more slowly and makes fewer, graceful turns before entering the water. This is an illustration of the conservation of angular momentum.

A pirouetting skater is another example. With the arms outstretched the skater spins slowly; pull them in and the rotation speeds up.

Angular momentum relates both to how fast a body is rotating and how compact or how spread out is the mass of the body around the rotation axis. **Conservation of angular momentum** means that, unless the body is interfered with, its angular momentum will not change. For an isolated body, left on its own, the angular momentum at the end of an event is the same as at the beginning.

It is important to define clearly the way in which the rate of rotation is measured. The rate of rotation of a body is called its **angular speed** and is measured in the number of radians turned through per second. The angular speed is usually denoted by the symbol ω (the lower-case Greek letter 'omega'), and has the SI unit of rad s^{-1}.

■ If a body rotates through one complete revolution, how many radians has it turned through?

❑ 2π (or 6.283) radians corresponds to one complete revolution of a body.

So, for instance, a body that undergoes one complete revolution in 1 s, will have an angular speed of 2π (or 6.283) rad s^{-1}. As this example suggests, it is often useful to be able to convert between the time taken for a body to undergo a full rotation (called the rotation period T) and the angular speed , and the two quantities are related by

$$\omega = \frac{2\pi}{T} \tag{9.1}$$

It is also useful to be able to convert between the frequency f with which a body undergoes complete revolutions and the angular speed

$$\omega = 2\pi f \tag{9.2}$$

QUESTION 9.6

Calculate the angular speeds of the following:

(a) A body that rotates through a half turn in one second.

(b) A body that undergoes a full rotation in 0.25 s.

(c) A body that rotates with a period of 4.0 s.

(d) A body that rotates with a frequency of 4.0 Hz.

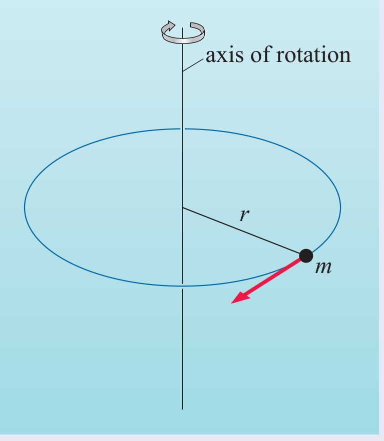


Figure 9.4 A simple system consisting of a mass m that is concentrated at a point that lies a distance r from the axis of rotation.

The second factor that determines the angular momentum of a body is a quantity that describes how compact or how spread out is the mass of the body around the rotation axis. This is called the **moment of inertia** around that axis. A more compact body has a smaller moment of inertia than a more extended body of the same mass. We will not be concerned too much here with the derivation of moments of inertia, but we will consider the following simple situation that illustrates how moments of inertia change if the distribution of mass changes. Figure 9.4 illustrates a system that consists of a mass m that is concentrated at a point that is a distance r from the axis of rotation. In this case the moment of inertia is given by $I = mr^2$. If, for example, the system shown comprises a 1 kg mass that rotates at a distance of 2 m from the axis, then its moment of inertia would be 4 kg m^2. If the system is made 'more compact', by reducing the distance from the axis to 1 m, the moment of inertia would drop to a value of 1 kg m^2. Note that the equation given here relating the moment of inertia to mass and distance applies only to this simple case: for other distributions of mass, such as that found within a star, the moment of inertia will be given by a different equation. Even so, the general principle still holds that if a distribution of mass is made more compact with relation to the axis of rotation, the moment of inertia will decrease.

The magnitude of the angular momentum L is related to the angular speed ω and the magnitude of the moment of inertia I by

$$L = I \times \omega \tag{9.3}$$

The diver has smaller moment of inertia when tight-tucked and so must have a larger angular speed (must turn faster) to keep the angular momentum constant. With arms outstretched the skater has larger moment of inertia and so must pirouette more slowly than with arms drawn in. Because the angular momentum is conserved, the angular speed can change only if the moment of inertia changes.

■ Returning to the system shown in Figure 9.4: as before, the system initially comprises a 1 kg mass at a distance of 2 m from the axis of rotation, and changes such that the distance of the mass from the axis of rotation becomes 1 m. If the system is initially rotating, would you expect its angular speed to increase or decrease as a result of this change?

❑ As a result of the change of distribution of mass, the moment of inertia has decreased. By the conservation of angular momentum, the angular speed must increase. (In fact, because the moment of inertia has decreased by a factor of 4, the angular speed must *increase* by a factor of 4 for angular momentum to be conserved.)

When the core of a supergiant collapses, its moment of inertia drops dramatically and hence the star spins up. To give a feel for the size of the effect, suppose that the Sun collapsed to the size of a neutron star; how rapidly would it be rotating then? If angular momentum is conserved

$$I_\odot \omega_\odot = I_\mathrm{n} \omega_\mathrm{n} \tag{9.4}$$

where the subscript n denotes the quantities for the neutron star. The moments of inertia are:

$$I_\odot = 6 \times 10^{46}\ \mathrm{kg\,m^2} \quad \text{and} \quad I_\mathrm{n} = 10^{38}\ \mathrm{kg\,m^2}$$

The Sun rotates on its axis once every 25.5 days, hence its period of rotation is

$$T_\odot = 25.5 \times 24 \times 3600\ \mathrm{s} = 2.20 \times 10^6\ \mathrm{s}$$

Therefore $\omega_\odot = \dfrac{2\pi}{T_\odot} = \dfrac{2\pi}{2.20 \times 10^6}\ \mathrm{rad\,s^{-1}}$

So $$\omega_\mathrm{n} = \frac{(I_\odot\, \omega_\odot)}{I_\mathrm{n}} = \frac{2 \times \pi \times 6 \times 10^{46}}{2.20 \times 10^6 \times 10^{38}}\ \mathrm{rad\,s^{-1}}$$
$$= 545\pi\ \mathrm{rad\,s^{-1}} (= 1.71 \times 10^3\ \mathrm{rad\,s^{-1}})$$

The period of rotation of the neutron star is

$$T_\mathrm{n} = \frac{2\pi}{\omega_\mathrm{n}} = \frac{2\pi}{545\pi}\ \mathrm{s} = 3.67 \times 10^{-3}\ \mathrm{s}$$

Therefore the neutron star rotates on its axis in about 4 milliseconds.

In fact it is not the Sun, but between 1.4 and about 3 solar masses in the centre of the supergiant that collapses to become the neutron star. While the values we have used in the calculation may not be strictly relevant, they are estimates that are reasonable to within an order of magnitude (i.e. within a factor of ten). So this calculation indicates that we would expect a newly formed neutron star to be spinning rapidly.

So now we see that neutron stars are small objects, predominantly made of neutrons, with high density and large gravitational fields, which rotate extremely rapidly. Do they have yet more unusual features?

We have seen how the rotational properties of the star become concentrated and produce rapid spin as the star collapses. In an analogous manner, any magnetic field that there was in the core of the supergiant would become intensely concentrated in the collapse. Once again, let's suppose that it is the Sun that shrinks to form a neutron star, and ask what would happen to the Sun's magnetic field strength in that process.

We saw in Chapter 2 (Box 2.2) that we can represent magnetic fields by lines – the direction of the lines gives the direction of the field, and the strength of the field is shown by how closely packed they are (that is, by the number of lines per unit area). Figure 9.5 shows how the magnetic field of a star changes as the star shrinks. The magnetic field strength, in SI units, is measured in tesla (T). At the Earth's surface the magnetic field strength of the Earth is about 4×10^{-3} T. The Sun has a general magnetic field strength at the solar surface of about 2×10^{-4} T, which we can think of as being through a cross-sectional area of $\pi R_\odot^2$. If the

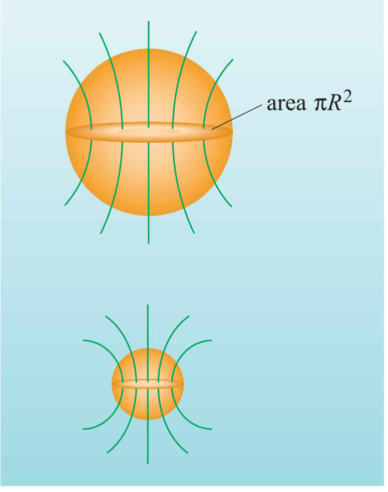


Figure 9.5 The magnetic field of a star through a cross-sectional area of πR^2, and how it becomes concentrated as the area shrinks.

radius of the Sun were to decrease, the magnetic field would become compressed (or concentrated), and its strength would increase as the cross-sectional area decreased. So the magnetic field strength of the neutron star would be larger by the factor $R_{\odot}^2/R_n^2$, where R_n stands for the radius of the neutron star. This factor is equal to $(7 \times 10^5)^2/10^2$, or about 5×10^9. So the expected field of the neutron star is $(2 \times 10^{-4}\,\mathrm{T}) \times (5 \times 10^9)$, or about 10^6 T. This is an enormous magnetic field! In fact it is an underestimate – for reasons that are beyond the scope of this book we believe that the magnetic field of a neutron star can be 10^8 T or even 10^9 T.

So neutron stars are small dense objects, rich in neutrons, with huge gravitational and magnetic fields, and they carry all this round with them as they spin many times per second. But that does not complete the list of bizarre properties that neutron stars possess. Neutron stars stretch physicists' understanding of material at high densities, test Einstein's General Theory of Relativity, and produce copious radiation in ways that are not yet understood.

9.3.1 Pulsars

Not surprisingly, most astrophysicists had never dreamt that such unlikely objects as neutron stars could exist. There were a few notable exceptions to this statement, such as the famous physicist Robert Oppenheimer – but they were not taken too seriously! The unexpected discovery of neutron stars as pulsing radio stars in the late 1960s therefore produced some excitement and amazement. (A first-hand account of this discovery is given in Box 9.2, at the end of this section.)

ROBERT OPPENHEIMER (1904–1967)

Robert Oppenheimer (Figure 9.6) was one of the leading theoretical physicists of his time. He was born and brought up in the United States, but studied in Europe as quantum mechanics was being developed. He returned to the States in 1929 and throughout the 1930s he worked on various topics in theoretical physics, including a study, with George Volkoff, of the nature of neutron stars. In 1942 he was appointed as director of the Manhattan project, with the aim of developing an atomic bomb. His management skills were no less impressive than his talent for physics: he successfully steered a disparate group of scientists, technicians and military personnel to achieving this goal.

Figure 9.6 Robert Oppenheimer. (Caltech)

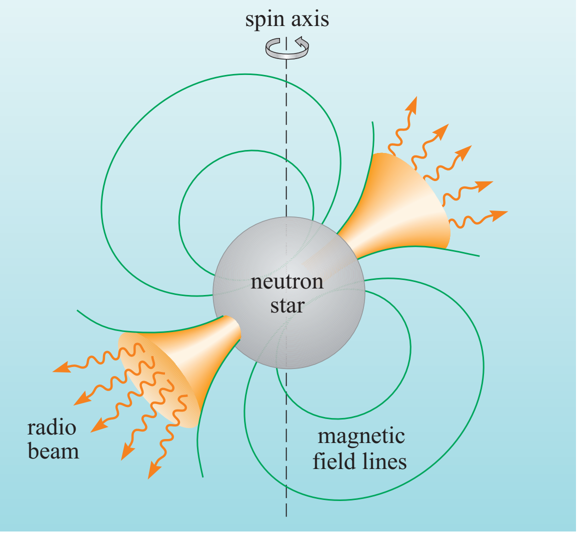


Figure 9.7 A schematic illustration of how a rapidly spinning neutron star produces a beam of radio waves.

The neutron star, swinging its immense magnetic field around each time it rotates, behaves like a huge lighthouse. Some distance away from the surface of the neutron star, electrons that are trapped in the magnetic field generate radio waves by the synchrotron process (Section 8.4.1). These radio waves are emitted in a beam whose direction is determined by the magnetic field, and this beam is swept around by the neutron star as it spins. The essential ingredients in producing the radio signal are the intense magnetic field and the rapid rotation; it is probably also important that the magnetic axis is at an angle to the axis of rotation as shown in Figure 9.7.

At this point it may help you envisage what is happening if you carry out a demonstration with a pair of scissors (preferably straight-bladed ones) as shown in Figure 9.8. Fix the blades open with sticky tape and twirl them about one shaft, which is held upright. With a bit of experimenting, you should be able to find a position for the scissors and an appropriate opening angle for the blades so that as you twirl the scissors there will be one point in each revolution where the slanted blade is point-on to you and you see right along its length (Figure 9.8).

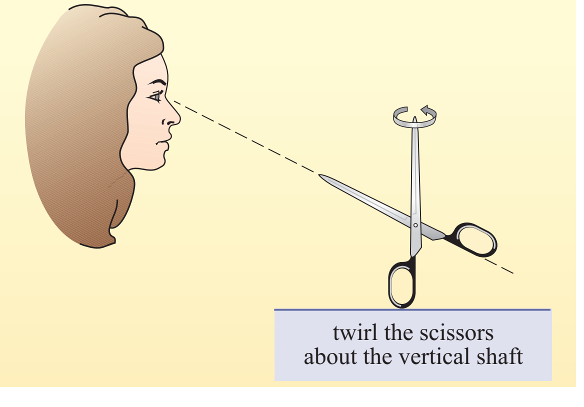


Figure 9.8 A demonstration using a pair of scissors, of the visibility of the beam of radio waves from the neutron star.

Similarly with the neutron star; if the relative orientation of the Earth and the neutron star is correct then, once in every revolution of the star, a line of sight from the Earth will look along the beam of radio waves.

- ■ What happens if the orientation of the Earth and the neutron star is not right?
- ❑ The radio beam misses the Earth.

- ■ If a neutron star rotating at four times a second is orientated so that its beam sweeps across the Earth, how many flashes of radio waves per second are received at Earth from this beaming star?
- ❑ The beam sweeps across the Earth every time the star rotates. So if the star rotates four times a second then the observer on Earth with a suitable receiver will detect four pulses per second of radio emission.

An observer on Earth with the appropriate radio-receiving equipment can detect the signal produced by a suitably aligned neutron star. The signal received is a string of regular pulses, a set of equally spaced bursts of radio emission as illustrated in Figure 9.9. These neutron stars are called **pulsars** – the name is an abbreviated form of *pulsating radio source*, although it should be noted that the neutron stars themselves do not pulsate but, as we have seen, they do produce pulses of emission.

QUESTION 9.7

It is believed that the time-averaged radio luminosity of a pulsar is about 10^{20} W. Compare the signal picked up from a pulsar at a distance of 10 kpc with that detected from a 100 kW radio transmitter 100 km away.

The accidental discovery of radio pulses from one of these objects caused considerable surprise. First, the repetition rate of the pulses (typically several per second) was much faster than anything previously known in astronomy. An object cannot change its brightness in a time less than the time it takes light to travel across the object. If something is producing (say) four pulses per second then it must be less than a quarter of a light-second across.

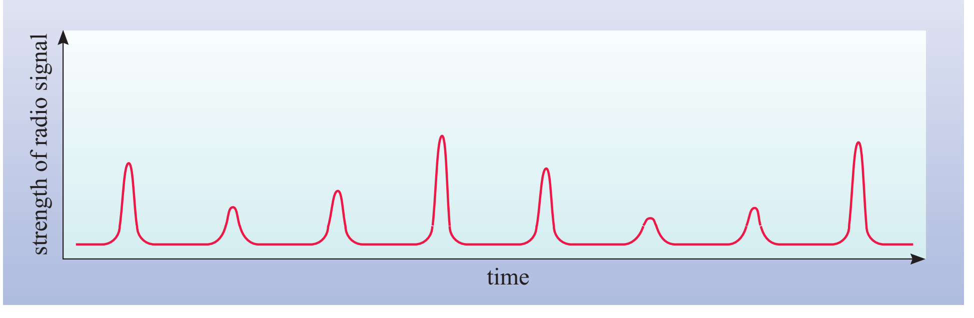


Figure 9.9 The radio signal received from a pulsar.

■ How far is a quarter of a light-second? How does that distance compare with the size of the Sun?

❑ A quarter of a light-second = 1/4 (3×10^8) m = 75 000 km. This is about a tenth of the solar radius.

The only objects of that sort of size or smaller that were known at the time were not normally radio emitters, and certainly not rapidly pulsed radio emitters.

The second cause for surprise was that the pulse rate was accurately maintained. This meant that, whatever the source was, it had large reserves of energy so that it could radiate pulse after pulse after pulse without showing any sign of slowing. If an object has large energy reserves, that usually means it is big.

So the object producing these radio pulses was big, and yet it was small!

This is a good demonstration of the need for precision in scientific language. Our use here has been a little loose and resulted in a conundrum. Let's sharpen up the terminology a little.

■ In what respect is the source of the radio pulses small? (Small in mass, in diameter?) And in what respect is it big?

❑ It is small in radius, in overall dimension. Our deductions about it being big came from noting that it must have considerable energy reserves. Most likely therefore it is big in the sense of being massive.

With hindsight (our best developed faculty!), we can see that neutron stars fit the bill exactly – they are very dense so they are both small in radius and massive.

There are now well over 1000 pulsars known; they lie far outside the Solar System but within the bounds of our Galaxy (the Milky Way). If their positions in the Galaxy are plotted they tend to lie in the nearer half. This distribution is apparent, not real; there are pulsars throughout the Galaxy, we believe, but they are sufficiently weak that we can only detect the nearer ones.

All the pulsars *emit* a beamed signal *continuously* at radio wavelengths which we *receive* as a stream of regular *pulses*. The pulse period is unique to each pulsar. The fastest produce pulses at a rate of hundreds of times per second, the slowest have periods of several seconds. All are believed to have been formed in Type II supernova explosions, although only a handful have an unambiguous association with a supernova remnant, so their origins are still under investigation.

Some pulsars can be very good time-keepers. As you will see below, the pulse periods of all (radio-emitting) pulsars are gradually getting longer. However once this effect is accounted for, the regularity of pulses from some pulsars can match the time-keeping from atomic clocks. International standards of time are defined by networks of atomic clocks and such systems are able to keep time to an accuracy of about 1 part in 10^{14} – this corresponds to uncertainty in time measurement of 1 μs over a period of about 3 years. The pulsars that have very short periods (typically of a few milliseconds) appear to be very smooth running, and some examples of this type of pulsar have been found to keep time as well as atomic time standards. Indeed, it has even been suggested that a combination of such pulsars could be used to define a new time standard that would be more accurate than the atomic clock networks that are currently in use.

QUESTION 9.8

An accuracy of 1 part in 10^{14} corresponds to how many seconds per century?

When we remember that the pulse period is (presumably) the rotation period of the neutron star, then these accuracies are not so surprising, for it takes a lot of energy to change the rotation rate of a star. However, the energy radiated comes ultimately from the rotational kinetic energy of the neutron star (although we do not yet understand exactly how). We can, through studying changes in the pulse period of the neutron star, monitor its loss of rotational energy as the pulsar ages.

Putting together all the available information, the picture we have is of a neutron star formed in a supernova explosion, initially rotating tens of times per second, but slowing as the star loses energy. After about a million years it will be a middle-aged, typical pulsar, with a pulse period of around 0.5 second. It continues to slow as it ages, until the mechanism for generating radio waves ceases to be effective when the star is rotating only once every few seconds, and the radio emission stops. The pulsar then becomes invisible, some 10^7 or 10^8 years after the supernova exploded.

■ What sort of object is left when the pulsar has stopped pulsing?

❑ We are left with a slowly rotating neutron star which is too faint to be detectable.

Considering that the supernova explosion was almost totally devastating, it is amazing that there should have been this lively object left. What is even more amazing is that, for some pulsars, the run-down just described is not the end – for some there is a rejuvenating mechanism that stirs them into life yet again!

Later in this chapter we shall discuss briefly interacting binary systems – examples of stars that are paired with a companion, and so closely paired that they affect each other's evolution. If a pulsar is paired in this manner then it is possible for its companion to transfer matter on to the pulsar, and transfer it in such a way that the pulsar is made to rotate faster. This way, we believe, the rapidly rotating pulsars that have periods of milliseconds or tens of milliseconds have been produced.

While the pulsar's gravitational field is drawing material off the companion and spinning up, several other things are happening. First, any radio radiation that might be produced at this stage is blanketed by the material streaming between the companions and so no radio pulses are seen. Secondly, the transferred material is compressed as it approaches the compact neutron star and is heated. Often it is heated so much that there is copious emission of X-rays. Most of the strongest X-ray sources in our Galaxy are of this kind and such is their strength that examples in other galaxies, external to our own, can also be seen by X-ray telescopes. These X-ray sources will be considered in more detail in Section 9.5.

BOX 9.2 THE DISCOVERY OF PULSARS

Figure 9.10 Jocelyn Bell Burnell, who together with Antony Hewish discovered pulsars in 1967. She later went on to become Professor of Physics at the Open University, a post that she held until 2001.

The following account of the discovery of pulsars was written by Jocelyn Bell Burnell (Figure 9.10), who, as a research student supervised by Antony Hewish, was involved with the discovery of pulsars in 1967.

In the mid-1960s Tony Hewish, a radio astronomer at the University of Cambridge (UK), was awarded a grant to build a special radio telescope to map the quasars in the sky visible from Cambridge and to determine their angular diameters. A full discussion of quasars is beyond the scope of this book, but briefly they are powerful radio sources that are believed to be in the distant reaches of the Universe; studying them gives valuable information on the Universe at an earlier age.

Quasars apparently have very small angular diameters, but Tony Hewish was exploiting a newly discovered technique which allowed these diameters to be determined. It had been noticed that the signal from some radio sources tended to fluctuate rapidly – they 'twinkled', or scintillated – and these were all quasars. The larger angular diameter radio galaxies did not show this fluctuation. The scintillation is produced by turbulence in the solar wind; detailed study of the scintillation gives the angular diameter of the quasar.

The first purpose of the experiment was to scan the sky for objects that scintillated – they were presumed to be quasars. The scintillation is a rapid flickering and so the telescope had to be able to follow rapid variations in the

radio signal. If the signal were to be detectable the radio telescope had to have a large collecting area. The telescope Tony Hewish designed covered 4.5 acres (which is an area that could accommodate 57 tennis courts). I joined Tony Hewish as a research student just as construction of this telescope was about to start. We put up over a thousand posts and strung more than 2000 antennae like TV aerials between them. The whole thing was connected by 120 miles of wire and cable. It took five of us two years to build; when finished it looked like a hop field, but it worked beautifully (Figure 9.11).

The construction was finished in mid-1967 and the construction crew melted away, leaving me to operate the telescope as it surveyed the sky for scintillating quasars. Computing power was very limited so the telescope output was on pen chart, 96 feet of it every day. As a mere research student the job of analysing these charts fell to me. As the telescope repeatedly scanned the sky it detected the quasars, but also, inevitably, it picked up interference from local sources, and one of the skills quickly acquired was the ability to distinguish between them on the charts.

However, after a few weeks' operation I realized that there was, very occasionally, a third type of signal. When present it occupied about a quarter-inch in the four hundred feet it took for a complete sky scan, and it wasn't always present. After a few sightings it clicked that this curious signal (nicknamed a piece of 'scruff') had been seen before *from the same part of the sky*. Curiosity raised, we decided to explore further, but at that point the 'scruff' faded and for a month could not be detected! Finally, perseverance paid off and a signal like that in Figure 9.9 with a pulse period of 1.33 seconds was traced out by the chart recorder pen.

Figure 9.11 The radio telescope used in the discovery of pulsars (the upright posts are about 2.5 m high). (G. Pooley, University of Cambridge)

Discoveries are rarely straightforward, and this is where our problems began. The pulses were too fast and too accurately maintained to be any known type of star, so it seemed logical to search for their origin within our equipment. No fault could be found, and when a colleague and his research student using their own telescope and receiver also picked it up this suggested its origin was beyond the observatory. It was suspiciously like a man-made signal, but when we found that it kept a fixed place among the stars that seemed to rule that out. We dubbed it LGM, for Little Green Men, and argued that if it were another civilization signalling to us they would probably be on a planet orbiting their star. Through studying accurately the pulse arrival times, we should be able to detect the Doppler effect as their planet went round their star. This experiment did indeed find a Doppler effect, but it was that due to the Earth orbiting the Sun. (Remember the Doppler effect works for movement of the observer as well as for movement of the source.) Using a technique called radio dispersion, we estimated the distance of the source as 65 parsecs – well beyond the Solar System, but well inside the Milky Way.

Several months had elapsed by this time (and several thousand feet of survey chart paper accumulated) and we had reached the point where we didn't really believe it was a signal from little green men, but we didn't have a sound physical explanation to put forward instead. We were wondering what to do next, when routine scanning of the charts surveying a totally different part of the sky suggested that there might be a second source of scruff-like signals. Difficult observations at the dead of night just before Christmas confirmed the pulsing signal – this time with a period of 1.25 seconds and of course from a different direction in space.

This discovery was much more exciting because it looked as if we really had found a new kind of star; it was highly unlikely that two lots of little green men would both choose to signal at the same time to an inconspicuous planet, both using a non-ideal method of communicating. When the third and fourth examples were found just after Christmas 1967 it became clear that these had to be stars, but it was probably another six months before the astronomical community agreed that these objects had to be neutron stars.

9.3.2 The detection of non-pulsing neutron stars

In the previous section we saw how some neutron stars, those that emit steady pulses at radio wavelengths, can be detected as pulsars. Here we briefly consider why it is that neutron stars are so hard to detect by any other means, and examine a remarkable case in which a neutron star that is *not* a pulsar has been detected.

The most direct method of observation of a neutron star would be to measure the thermal emission from its surface. Neutron stars are formed in a very hot state; it is believed that their initial surface temperatures are over 10^8 K. They cool to about 10^6 K over a few thousand years and reach a surface temperature of about 10^5 K about a million years after formation. The emission from the surface of a neutron star is expected to follow a black-body spectrum, and hence its luminosity will be given by Equation 3.9.

QUESTION 9.9

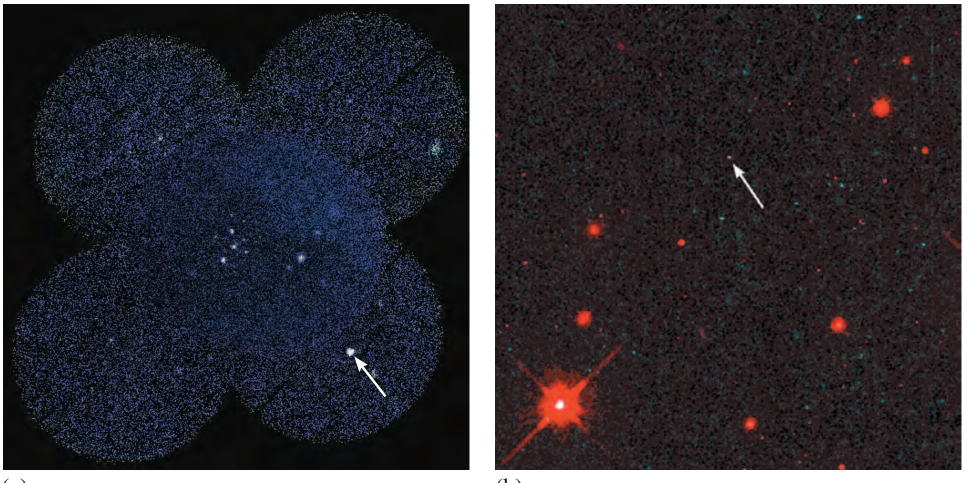
A neutron star has a radius of 10 km and a surface temperature of 5×10^5 K.

(a) In which part of the electromagnetic spectrum will the peak of the black-body emission from the neutron star occur?

(b) Calculate the luminosity of the neutron star. Express your answer in terms of the solar luminosity.

As the answer to Question 9.9 shows, isolated neutron stars may be expected to be low-luminosity sources that have a peak in emission in the soft X-ray or extreme-UV parts of the electromagnetic spectrum.

Unfortunately, the number of such neutron stars that could be expected to be found from surveys of the sky in the X-ray band is very low. Despite this, an isolated neutron star was found accidentally in 1996. Earlier, in 1992, the field of view of an X-ray observation of an interstellar cloud was found to include an unidentified source that was given the rather anonymous name of RX J185635–3754 (Figure 9.12). Initial follow-up observations revealed that the source has a black-body spectrum with a temperature of 6.6×10^5 K and that emission comes from a star with a radius of about 14 km. The only plausible interpretation of those observations is that the star was a neutron star. However, there have been observations that suggest that its true radius is actually only about 6 km. If this were the case, then it might be the first evidence for the existence of an object that is yet more extreme than a neutron star – a **quark star**. Quarks are the fundamental particles that make up neutrons and protons: each neutron and each proton comprises three quarks. In a quark star, it is hypothesized that neutrons lose their individual identities, and that matter exists as a sea of quarks. The theoretical properties of such objects are very poorly understood, and it is not even clear whether such objects should actually exist. Thus, this object could be highly significant. However, the evidence that RX J185635–3754 is a quark star is far from conclusive, and most astronomers require much more convincing proof that it is anything other than a 'normal' neutron star.



(a) (b)

Figure 9.12 Images of the field-of-view that contains the isolated neutron star RX J185635–3754. (a) In the soft X-ray band, the neutron star is the bright source in the lower right-hand part of the image. (b) An image made by combining two visible wavelengths observed with the Hubble Space Telescope. The colour of a star in the image corresponds to its temperature. An extremely hot source, that is interpreted as a neutron star is visible as the white object in this image. (The blue spots are due to cosmic rays hitting the detectors of the telescope.) The neutron star is estimated to be about 61 pc from the Sun. (F. Walter (University of New York at Stony Brook)/NASA)

9.4 Black holes

Case study 1

Imagine a neutron star, a massive one as neutron stars go, close to the maximum mass that can be supported by neutron degeneracy pressure. The star's gravity pulls down onto it some of the gas that is in the vicinity. The extra material takes the mass of the star over the limit, so that the gravitational contraction now overwhelms the neutron degeneracy pressure. The neutron star collapses.

Case study 2

Imagine now the core of SN 1987A. A burst of neutrinos gave a clear indication that a neutron star had been formed, but there has been no subsequent sign of such a star's existence. Suppose the neutron star did exist, briefly, and that it was a massive neutron star, close to the maximum mass that could be supported by neutron degeneracy pressure. The supernova explosion has expelled a lot of the surrounding material, but it has been estimated that the neutron star's gravity could cause about $0.1M_{\odot}$ of the material to fall back onto the star in the first few hours after the explosion. If this added material caused the gravitational force to exceed the neutron degeneracy pressure then the neutron star would collapse under its own gravity.

Case study 3

Picture now a particularly massive supergiant with a large iron core near the end of its evolution. As described earlier (Section 8.3) when the core contraction starts the iron nuclei break up, electrons merge with protons to form neutrons and in a matter of seconds the inner core has collapsed to neutron star densities. Suppose, however, that the collapsing inner core is more massive than in the case considered in Section 8.3, so massive that the neutron degeneracy pressure cannot withstand the gravitational force. The collapse will not halt at nuclear densities but will continue.

These three case studies all point to the same question: what happens when the gravitational force is greater than the force provided by the neutron degeneracy pressure? Reviewing the story so far, we see that in stars too massive to be white dwarfs, where the electron degeneracy pressure was insufficient to support the star, collapse to another form of matter (the neutron-rich material) ensued. The existence of this other stable form of matter at higher densities allowed the collapse to halt and produced an unusual kind of star.

Will something similar happen in this case, in stars too massive to be neutron stars? Is there another kind of particle and another kind of pressure that will come into play and halt the contraction? We have already mentioned the possibility of quark stars, and the fact that their existence is not yet proven. Even if they do exist, they would also have a limiting mass, above which they would collapse.

There appears to be no mechanism that would halt the collapse of a very massive star. It seems that there is no force that can resist the gravitational contraction. There is nothing to stop the star shrinking under gravity.

The strength of the gravitational force on an object of mass m at the surface of a star of mass M_* and radius R_* is

$$F_{\mathrm{g}} = \frac{GM_*m}{R_*^2} \tag{9.5}$$

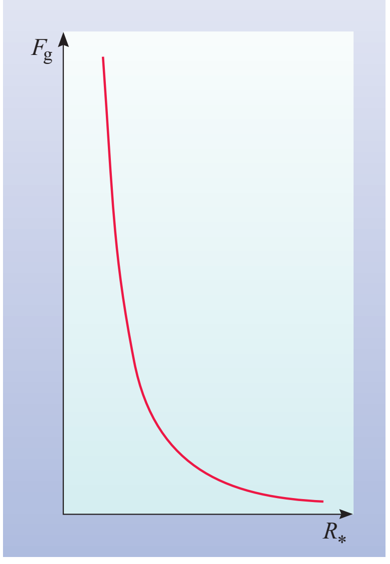


Figure 9.13 How the strength of the gravitational force at the surface of a star depends on the radius of the star.

■ What happens to the gravitational force at the surface of the star if the radius of the star decreases?

❑ As the radius of the star (R_*) diminishes, the gravitational force at its surface, F_g, increases, as shown in Figure 9.13.

The increase in F_g makes it less likely that there can be a force that can effectively resist this gravitational force. More importantly, the increase in F_g produces yet more contraction…which of course increases F_g, which produces more contraction! (Strictly speaking, as the force increases there comes a point where this formula ceases to apply. However, it still serves as an indication of what will happen.)

So the collapse continues relentlessly, apparently until the star has been squashed into an infinitely small space, that is, until it has become a point mass.

■ If the volume of the star has become infinitely small, what has happened to its density?

❑ The density has become infinitely high; the star has zero volume but finite mass!

This is called a singularity; it is a concept that is mathematically and physically difficult to handle (and perhaps you feel that in other ways too it is difficult to handle!) so there is discussion about whether quantum effects or some other effects come into play when the density is extremely high, but not quite infinite, so as to avoid the formation of a singularity. The details need not concern us here – the star collapses down to something not far short of a point, if not an actual point.

During the collapse the gravitational effects increase enormously and we now turn to consider these effects. We shall work with a quantity called the **escape speed**, which is given by:

$$v_{esc} = \sqrt{\frac{2GM}{R}} \qquad (9.6)$$

where M is the mass of the (spherical) body from which escape is desired, and R is its radius. Note that the speed of escape does not depend on the mass of the escaping object – it is the same for a ball or a rocket. For escape from the surface of the Earth it is 11 km s^{-1}.

■ As a star of mass M shrinks, how does its escape speed change?

❑ The escape speed increases (apparently without limit as the star's radius shrinks to approximately zero).

A full treatment of black holes requires an understanding of Einstein's Theory of General Relativity, which is beyond the scope of this book. However, you may be aware of one of the conclusions of relativity theory, which is that nothing can travel faster than c, the speed of light in a vacuum.

- ■ Can you guess what will happen when the star shrinks sufficiently that the escape speed reaches the speed of light?
- ❏ It looks as if for radii smaller than this, things will not be able to escape from the collapsing star, because to do so would require speeds greater than c, which are not possible.

The radius where the escape speed equals the speed of light is a critical radius in the collapse of a star, called the **Schwarzschild radius** (pronounced Sh-vartz-child). At radii smaller than this, no material can escape from the collapsing star. It also represents a point-of-no-return for the collapsing star itself – once this radius has been passed the collapse of the star cannot be halted. Furthermore, no light waves (or radio, or X-ray, or infrared, or any other electromagnetic radiation) can directly escape either. The collapsing star as it crosses the Schwarzschild radius becomes a **black hole**; black because no radiation gets out, and a hole because matter can fall in but cannot get out of it!

QUESTION 9.10

Derive an expression for the Schwarzschild radius (R_S) in terms of G, M and c.

QUESTION 9.11

Calculate the size of the Schwarzschild radius for a star of $1.0M_\odot$.

Although black holes are not luminous, their gravitational fields still exist. Anything that comes too close to a black hole is pulled towards it by gravity. Anything that is pulled closer than the Schwarzschild radius cannot escape; it is sucked in and squashed to (near) infinite density.

When something falls down a black hole do we see any change in the black hole? If we can ascertain the mass of the black hole (perhaps through measuring the strength of its gravitational field) then we would see that its mass has increased. The only other physical properties possessed by a black hole are its electric charge and its angular momentum. All other information about what went down a black hole is lost. One cannot tell whether it was a one kilogram bag of feathers or a one kilogram bag of lead that has just been swallowed by the hole.

Disembodied gravity is difficult to detect, so is there any observational evidence for the existence of black holes or are they a theoretician's dream (or nightmare)? Isolated black holes would be hard to see, but many stars are in binary systems; if one of the stars in a close binary had evolved into a black hole, then it would be possible to infer its presence from observations of the binary. It is this type of system that we shall consider in the next section.

9.5 Stellar remnants in binary systems

Most stars exist in binary systems or bigger groupings (Section 3.2.3). In many multiple star systems the stars are sufficiently far apart (more than 100 AU) that there is little interaction between the stars apart from their mutual gravitational influence on one another. However, there are systems in which the two stars orbit each other sufficiently closely that matter can be transferred from one star to another. The process of mass transfer has direct observational consequences and, over time, alters the evolution of both stars. Such binary systems are the subject of this section.

9.5.1 Interacting binaries – laboratories for studying stellar remnants

Before considering binary systems, let us first imagine what would happen if we could drop material directly onto an isolated star. Any process by which material is added to a star is termed **accretion**. If a mass m of material falls onto a star of radius R_* and mass M_*, then provided that the material starts from a position that is a long way from the star, the gravitational potential energy released will be $E_g = GM_*m/R_*$. Initially this would be released as the kinetic energy of the in-falling material, but on hitting the surface of the star, this would be converted into thermal energy and cause heating.

■ Imagine that we could drop 1 kg of material onto a $1.4M_\odot$ white dwarf and a $1.4M_\odot$ neutron star. For which type of star would the gravitational potential energy release be greatest?

❑ The energy released is given by $E_g = GM_*m/R_*$, but G, M_* and m are the same in both cases, so the larger amount of energy will be released in the case where R_* is smaller. Since the radius of a neutron star is much smaller than that of a white dwarf, it is accretion onto a neutron star that liberates most energy.

Hence for a given mass, the smaller the radius of star that material can fall onto, the greater the energy that can be released. So we might expect that accretion onto stellar remnants which have relatively small radii might produce energetic phenomena. At this point, you might be wondering how gravitational potential energy might be released in the case of accretion onto a black hole, since there is no surface for the in-falling material to strike. As you will see later, there is a mechanism by which accretion onto black holes can liberate copious amounts of energy.

There are two main processes by which material can be transferred from one member of a binary system to the other. As an introduction to the first type of mass transfer process, consider the situation described in the following question:

QUESTION 9.12

In a certain binary system, one of the stars is a white dwarf with mass $1.20M_\odot$ and radius $0.006R_\odot$ while the other is a main sequence star with mass $0.70M_\odot$ and radius $0.96R_\odot$. The centres of the two stars are a distance of $2.18R_\odot$ apart. Consider a blob of gas that lies on the line that connects the centres of the two stars and at the outermost part of the envelope of the main sequence star (i.e. it is

at a distance of $0.96R_{\odot}$ from the centre of the main sequence star). This blob is influenced by the gravitational attraction of both stars.

(a) Draw a diagram of this system that shows the direction of the gravitational forces acting on the blob.

(b) Compare the gravitational forces due to the two stars on the blob in this position. Which is the larger?

Question 9.12 indicates that at the surface of the main sequence star the white dwarf may exert a stronger force, and so it is quite possible to have material transferred from one star onto the other. There will be a number of points in the vicinity of the two stars where the blob of gas experiences *equal* gravitational pull towards the two stars; we did the calculation for a point on the line joining the stars, but there are, for example, points either side of this line where this is also true. In practice, the stars are rotating about each other and this complicates the analysis of forces. However, when the system is considered in a frame of reference that is rotating with the orbital period, it is still true that there are positions where a blob of gas experiences no net force. These are called **Lagrangian points** (the term Lagrangian, pronounced 'Lah-grahn-jee-an', refers to the French mathematician Joseph Louis Lagrange, 1736–1813). As far as transfer of material between the two stars is concerned, it is the Lagrangian point on the line joining the centres of the two stars that is of primary importance; this is called the **inner Lagrangian point**. Material that is positioned at the inner Lagrangian point is poised such that with a tiny push, it could fall either towards one star or the other. If one of the stars in the binary is large enough that its surface touches the inner Lagrangian point, then material can overflow this point and start to fall towards the other star.

The shape of the surface that a star occupies when it touches this point is not spherical: the influence of the other star and the rotation of the entire system result in a surface that is somewhat pear-shaped. This surface is called a **Roche lobe** and it represents the maximum volume that a star can occupy before it begins to transfer material through the inner Lagrangian point, and the process of mass transfer is called **Roche lobe overflow**. Roche lobes can be defined around any star in a binary system regardless of whether that star is actually filling the lobe. In diagrammatic representations of close binary stars such as that shown in Figure 9.14, it is usual to show the Roche lobes around both stars.

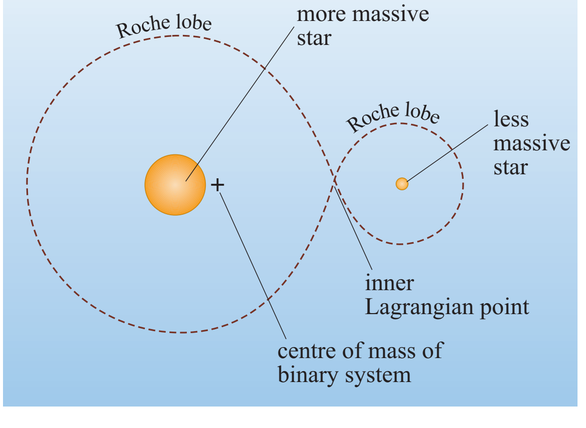


Figure 9.14 A cross-section through a close binary system; the dashed line shows the boundary of the Roche lobes.

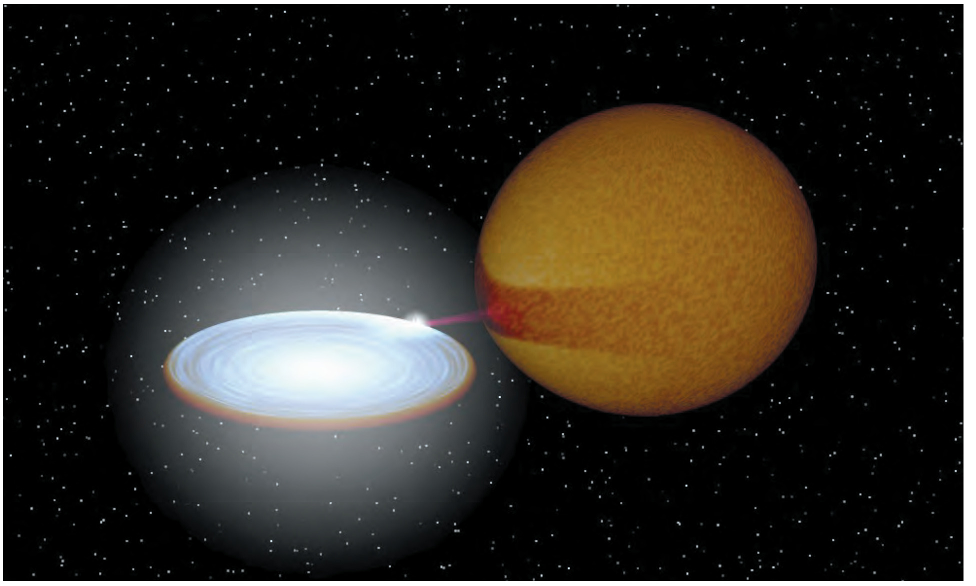


Figure 9.15 A simulated view of a binary system in which mass transfer occurs from a star with a relatively large radius by Roche lobe overflow on to a white dwarf. The material that is transferred forms a luminous accretion disc which can, as in this case, dominate the optical emission from the system. (The white dwarf, which is located at the centre of the accretion disc, cannot be discerned against the bright background of the disc.) (R. Hynes, University of Texas at Austin)

When Roche lobe overflow occurs, material is transferred through the inner Lagrangian point and enters the Roche lobe of the other star. Because of the conservation of angular momentum, such material does not fall directly towards this star, but preferentially heads to one side of it. If this material were in the form of a small solid test particle it would go into a highly elliptical orbit around the star. In reality, the material is in the form of a continuous stream of gas. This stream interacts with itself and forms a disc of material around the star, called an **accretion disc**, as shown in Figure 9.15. Interactions within the disc redistribute the angular momentum of material. Most matter in the disc loses angular momentum and consequently spirals down through the disc and onto the star. However, we saw earlier that angular momentum is a conserved quantity, so the angular momentum that is lost by the accreting matter must be transferred elsewhere. In fact, angular momentum is transferred to the relatively small amount of material that forms the outer parts of the accretion disc, and is then fed back into the orbital system of the binary through tidal interactions. So the accretion disc allows most of the matter that is transferred to move inwards towards the central star. In doing so, the gravitational potential energy of this material is converted into thermal energy and heats the disc.

Thus the accretion disc is a source of electromagnetic radiation. Most of the disc emits strongly in the optical and the ultraviolet parts of the spectrum and those parts of the disc that are closest to the stellar remnant tend to be a luminous source of X-rays. In addition, in the case of white dwarfs and neutron stars, there may also be strong X-ray emission from the surface of the stellar remnant as accreting material is dramatically brought to a halt. Thus an interacting binary that contains a white dwarf, neutron star or black hole will tend to be an X-ray source, and consequently they are generically referred to as **X-ray binaries**. These sources dominate the sky at X-ray wavelengths as Figure 9.16 shows.

A second mass-transfer process can occur where one star has a very strong out-flowing stellar wind; as it moves in its orbit, the other star captures some of the circumstellar material as indicated in Figure 9.17. Such a process is called **stellar wind accretion**. Strong stellar winds tend to be associated with high-mass stars, so binary systems in which this process is taking place often include a luminous star of spectral type O or B. Unlike the case of Roche lobe overflow, it is rather difficult

to predict whether an accretion disc will be formed as a result of stellar wind accretion. Furthermore, observations of stellar wind accreting systems do not unambiguously show the presence of accretion discs and so there is a lack of detailed knowledge about these systems.

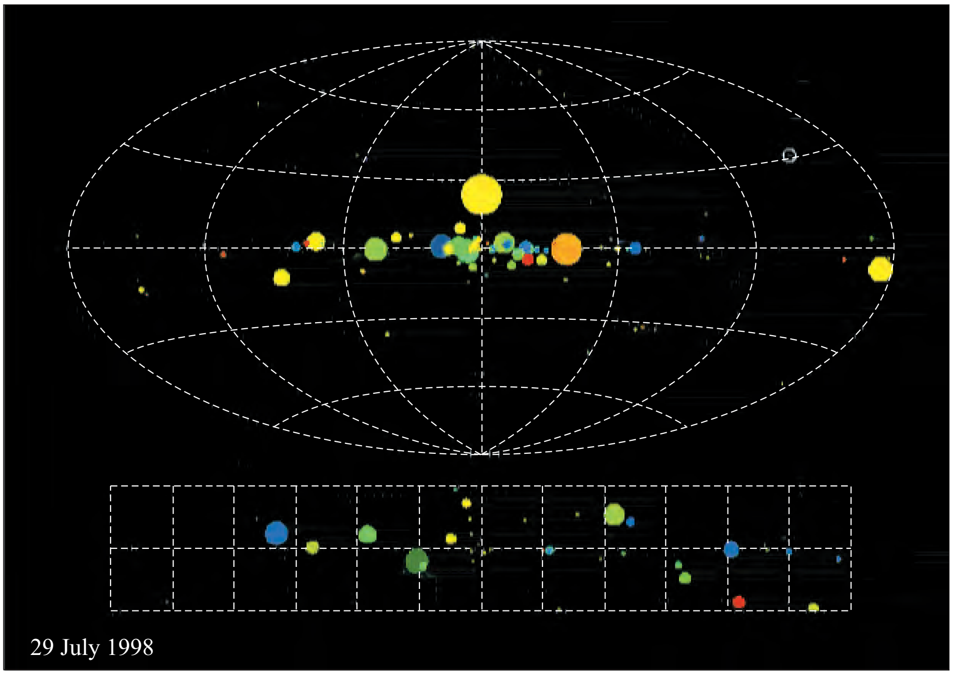


Figure 9.16 An X-ray map of the sky as it appeared on 29 July 1998 to an instrument on the Rossi X-ray Timing Explorer satellite. The upper map shows the whole sky: the centre of the map corresponds to the direction towards the centre of our Galaxy and the horizontal line across the centre of the map corresponds to the plane of the Galaxy. The lower map shows a central region ($60° \times 10°$ in extent) of the all sky map. The size of a circle indicates the intensity of the X-ray flux while its colour provides information about the spectrum of the X-ray source. Note that this map only shows the brightest X-ray sources – there are many more fainter sources which were not detected by this particular instrument. The most numerous sources in the map are X-ray binaries in which matter is transferred by Roche lobe overflow onto a neutron star. The very bright source that is positioned somewhat above the centre point of the map is one such source: an X-ray binary called Sco X-1 that is the brightest X-ray source in the sky. (M. Muno, Massachusetts Institute of Technology)

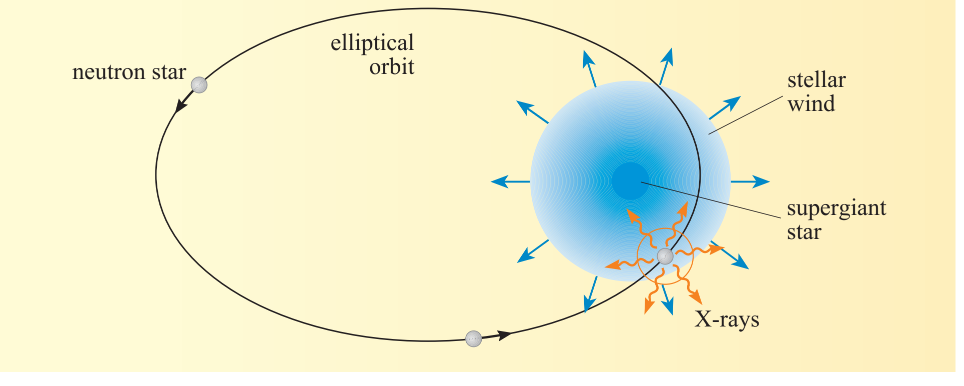


Figure 9.17 The process of mass transfer in which a stellar remnant 'captures' some of the strong stellar wind that emanates from a supergiant companion star. In this case the binary orbit is highly elliptical. The highest rate of accretion and hence X-ray emission occurs when the stellar remnant and the companion star are closest to each other.

9.5.2 Accretion onto white dwarfs – cataclysmic variables

Given the ubiquitous nature of white dwarfs, it is perhaps not surprising that the most common forms of interacting binary are those in which material is transferred to this sort of stellar remnant. Such systems are called **cataclysmic variables**, a name that reflects the often dramatic changes in luminosity that they exhibit. These changes are most prominent in the optical, ultraviolet and X-ray parts of the spectrum. In cataclysmic variables the mass transfer process is exclusively by Roche lobe overflow; there are no known cases of stellar wind accretion onto a white dwarf. There are several subclasses of cataclysmic variable, but two of the more important ones are dwarf novae and novae.

The **dwarf novae** are stars that show erratic outbursts in their optical emission. A typical outburst may involve a brightening of 2–5 magnitudes in a few days, followed by a slower decline to quiescent levels. Figure 9.18 shows the light curve for the dwarf nova SS Aurigae. The outbursts are not periodic, but reoccur over a timescale of weeks to months. The optical luminosity of these systems is dominated by emission from the accretion disc, and it is likely that the outburst arises from an instability in the disc. When the dwarf nova is in a quiescent state, matter is only able to pass through the accretion disc at a low rate and hence builds up in the disc. The outburst represents a change in the disc that suddenly allows the accumulated material to pass quickly through the disc hence giving a sharp increase in the luminosity.

A **nova** (sometimes called a classical nova) is also characterized by a sudden outburst in luminosity, but in this case the star brightens by more than 10 magnitudes (Figure 9.19). The outburst lasts for a matter of days or weeks before slowly returning to its pre-outburst level. The mechanism that drives nova outbursts is thermonuclear burning on the surface of the white dwarf. As a result of the process of mass transfer, hydrogen-rich material accumulates on the surface of the white dwarf. The density and temperature at the bottom of this layer increase over time until conditions are such that nuclear fusion of hydrogen can begin. This proceeds in a runaway fashion, leading to the observed outburst and the ejection of some of the material from the surface of the white dwarf.

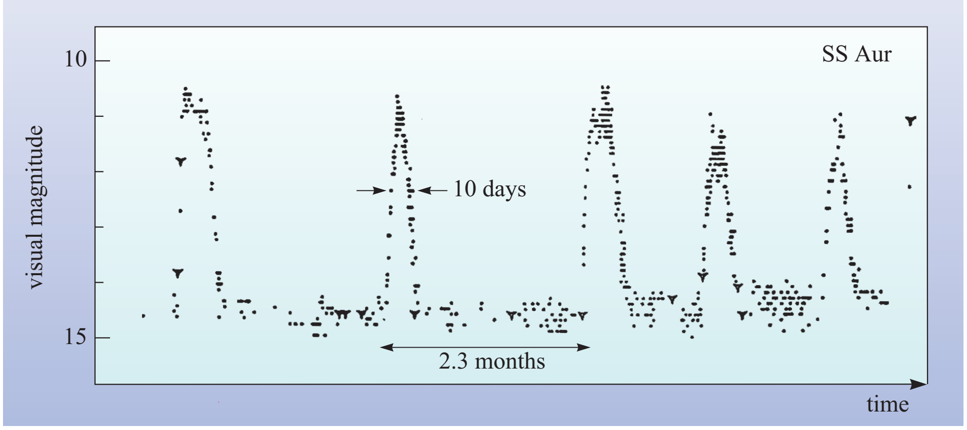


Figure 9.18 The visual light curve for the dwarf nova SS Aurigae. The data for this light curve were collected by amateur astronomers – this is an invaluable service for researchers who study cataclysmic variables. (F. A. Córdova and H. Papathanassiou from data provided by AAVSO)

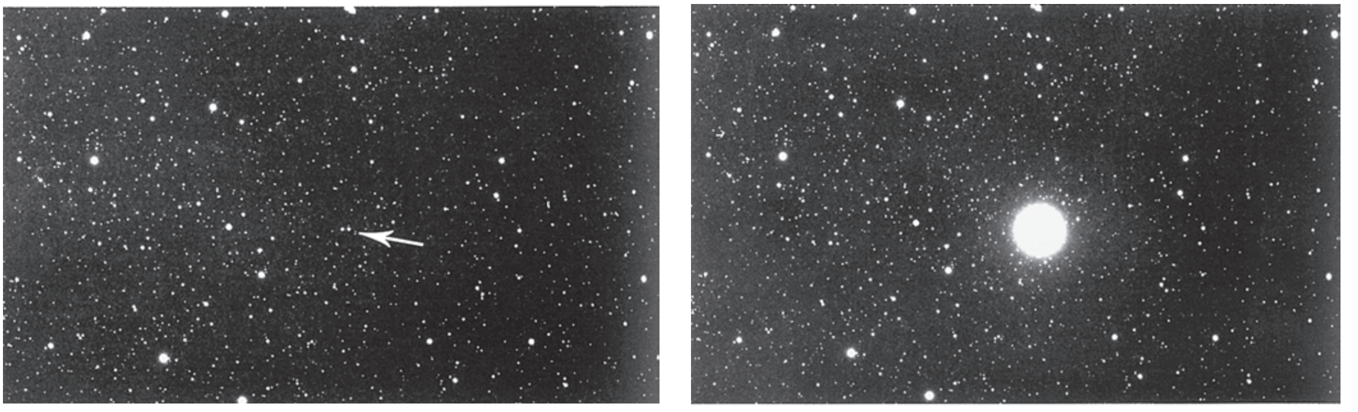


Figure 9.19 Nova Cygni 1975 erupted on 29 August 1975. (Left) Before and (right) after the nova outburst. (Lick Observatory)

9.5.3 Neutron stars in binaries

Neutron stars are found in binaries where mass transfer occurs both by stellar wind accretion and by Roche lobe overflow. It seems that the mass transfer process disrupts the radio emission that is observed in isolated pulsars, and radio pulses are not observed from these systems. However, accretion in these systems results in material being heated to over 10^6 K and consequently they tend to be luminous sources in the X-ray band. Since neutron stars typically have high magnetic field strengths and are rotating rapidly, it is not surprising to find that some neutron stars in accreting binaries show regular pulses in their X-ray emission, and are described as **X-ray pulsars**. The range of pulse periods in X-ray pulsars is wider than for radio pulsars – from a minimum of about 69 ms up to a maximum of over 800 s. The origin of the X-ray pulsations is linked to the interaction between the accreting material and the magnetic field of the neutron star.

■ The accreting material is in the form of a plasma. What would you expect this material to do as it enters the very high magnetic fields that are close to the neutron star?

❑ A plasma in a very strong magnetic field is forced to move along the magnetic field lines (Section 2.3.1).

This effect may disrupt the inner parts of an accretion disc (if one is present), and material will funnel down onto the magnetic polar regions of the neutron star. These regions will be heated by the impact of accreting material, and so they will emit more strongly than other parts of the neutron star. As in the case with radio pulsars, it is likely that the magnetic axis and the rotation axis of the neutron star are not aligned (as illustrated in Figure 9.20, overleaf), and so rotation of the neutron star gives rise to a modulated pattern of X-ray emission. However, not all binaries that contain neutron stars emit regular pulses; some emit rather weak pulsations that are not strictly periodic, and others simply show rapid flickering that has no periodic variability.

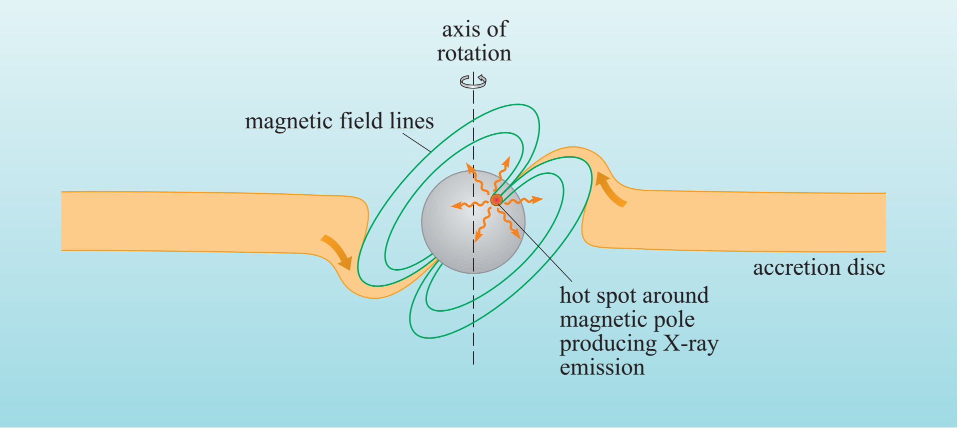


Figure 9.20 A schematic diagram of the inner part of an accretion disc (shown in cross section) and a neutron star. Note that the neutron star and accretion disc are not drawn to scale and that the inner edge of the accretion disc is hundreds of neutron star radii in diameter. The magnetic field of the neutron star affects the in-fall of accreting material – the inner edge of the accretion disc is disrupted by the magnetic field and consequently plasma funnels down the field lines. Hot spots form near the magnetic poles of the neutron star. Since the axis of rotation and the magnetic axis are not co-aligned, the rotation of the neutron star gives rise to modulation in X-rays.

The existence of neutron stars in any binary system, including those binaries that are too widely separated to be interacting systems, offers the possibility of measuring the masses of neutron stars. Thus, the rather poorly determined theoretical limit to the mass of a neutron star can, in principle, be tested against observation.

■ Given that no neutron star binaries are visual binaries, what physical property of the stars needs to be measured, and what is the other necessary condition that would allow the masses of the stars in the binary to be determined?

❏ It must be possible to measure the orbital speeds of each star and the system must be an eclipsing system (see Section 3.3.7).

In neutron star binaries it is often possible to measure the orbital speed of the companion star by spectroscopic means. The orbital speed of the neutron star cannot be determined by spectroscopic methods, since its radio or X-ray emission does not show sharp spectral lines. However, if the neutron star is a radio or X-ray pulsar, then its orbital speed can be determined by measuring the change in frequency of the *pulses* over an orbital cycle. This is because the Doppler effect (Box 3.1) applies to the pulses of emission from the pulsar, and the radial velocity can be found in a similar way to Equation 3.3,

$$v_r = c \times (f - f')/f' \tag{9.7}$$

where f and f' are the rest frequency and the observed frequency of the pulses. The pulses are pulses of electromagnetic radiation, so their speed is c – the speed of light.

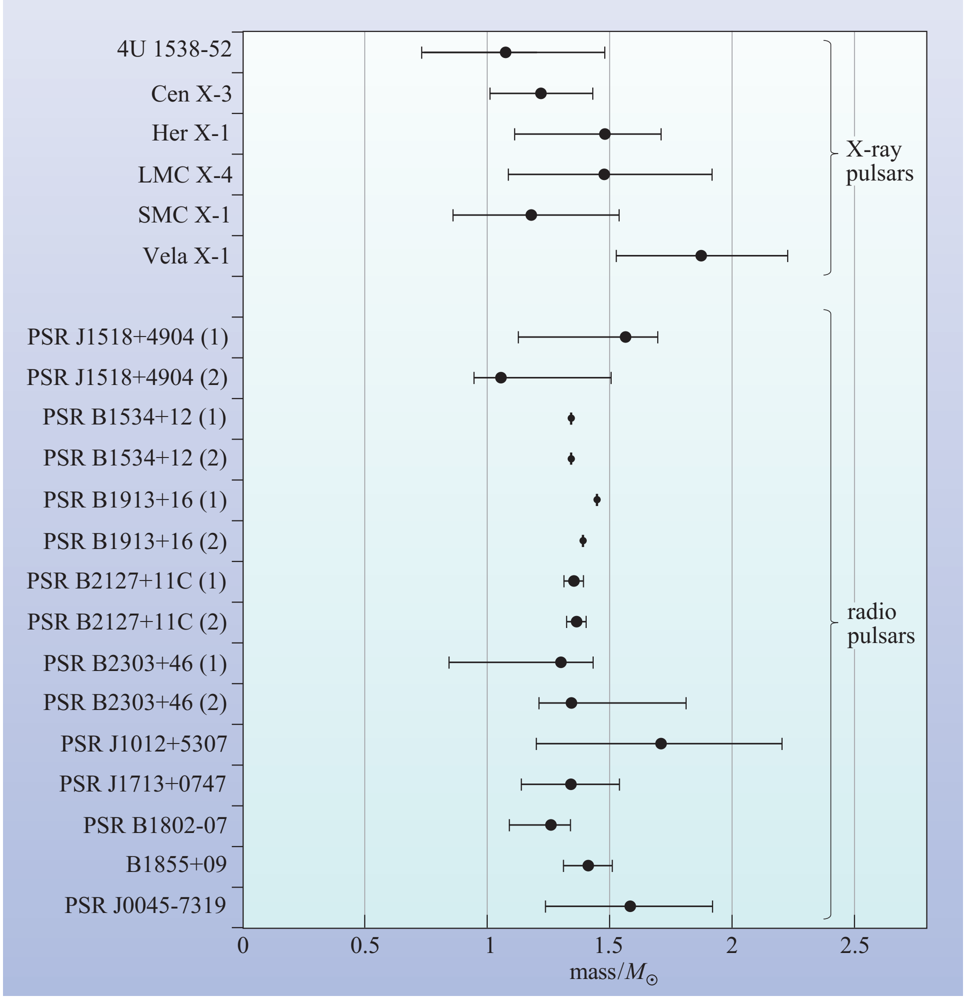


Figure 9.21 The measured masses of neutron stars. The upper six cases are X-ray pulsars that are in interacting binaries, the lower ten are radio pulsars that are in non-interacting binaries. In the case of radio pulsars, five of the systems are double neutron star systems, and the masses of each of these neutron stars (distinguished by (1) or (2) in the name) are shown. (Data compiled by S. Clark (University College London))

This type of analysis has been carried out for a number of neutron star binaries. Some of these are interacting binaries which contain X-ray pulsars and others are non-interacting binaries that contain radio pulsars. Figure 9.21 shows values of neutron star masses that have been obtained by such studies, and illustrates that they all lie close to a value of $1.4M_\odot$. Only a small number of masses have been measured in this way and future observations may reveal the existence of neutron stars with masses up to about $3M_\odot$, but equally, it may be found that the limiting mass is much closer to $1.4M_\odot$ than is predicted by current theories.

9.5.4 Black hole candidates

Observationally, the binary systems that are believed to harbour black holes are similar in some respects to interacting systems that contain neutron stars; they are bright X-ray sources that show substantial variability in their luminosity. The challenge to astronomers is to produce convincing evidence that such systems, which are called **black hole candidates**, cannot be explained by accretion onto a neutron star. Any source that exhibits regular pulsation is likely to be a neutron star: black holes have no magnetic field and so cannot produce modulated emission. This does *not* mean that any source that does not show pulsation must be a black hole; it is quite likely that some neutron star binaries do not produce pulsed emission.

- What property of a stellar remnant in an interacting binary *could* be used to rule out the possibility that it is a neutron star?
- Its mass: if the mass of a stellar remnant exceeded the maximum mass of a neutron star, then it could be concluded that the object is a black hole.

Since astronomers require overwhelming evidence that the remnant is not a neutron star, it is usual to accept the highest theoretical upper limit to the mass of a neutron star as the minimum mass that would prove the existence of a black hole. For this purpose, the mass limit is taken to be $5M_\odot$ although most astrophysicists believe that the true limit is substantially lower than this.

There are immense practical difficulties in carrying out measurements to determine the mass of black hole candidates. The first difficulty is the small number of such systems; only about twenty or so are known. Secondly, the method of determining masses that was described for neutron stars has to be modified for two reasons: there are no pulsations, and, none of the known systems show eclipses. The result of this is that while the mass itself cannot be determined without making certain assumptions about the binary system, a *lower limit* to the mass of the black hole candidate can be found. In many cases, there is no known optical identification of the system, and without optical spectroscopy of the mass-losing star, not even a mass limit can be determined. A final difficulty is that the sources that provide the highest lower limits to the mass of the black hole candidate are so-called 'transient' sources – for most of the time their X-ray emission is at a low level and the source is undetectable. It is only when these sources show outbursts that it is possible to identify them as black hole candidates. These outbursts last for a few weeks or months, but their occurrence is unpredictable, and the source may then return to a quiescent state for a period of many years.

A black hole candidate that has a high lower limit to its mass is a system called V404 Cygni. Outbursts of this source had been observed in the optical waveband by amateur observers in 1938 and 1956, and originally it had been classified as a nova (in fact, it was classified as a 'recurrent nova' – a star that seems to repeat nova-like outbursts over an interval of several years). In 1989 a luminous outburst was detected in the X-ray band which revealed that this was not a system in which accretion was occurring onto a white dwarf, but one in which the stellar remnant must be a neutron star or black hole. After the 1989 outburst had subsided, it was possible to make optical spectroscopic measurements of the mass-losing star, which was found to be a subgiant of spectral type K0. The orbital period of the system was measured as 6.5 days, and this led to a lower limit to the mass of the black hole candidate of $6.3M_\odot$. Since this is substantially above the maximum possible mass for a neutron star, the stellar remnant in V404 Cygni is generally accepted to be a black hole.

The firm lower limits to a range of black hole candidates provide good evidence that black holes of a few solar masses do exist. As mentioned above, the mass of a black hole candidate can be calculated if certain assumptions are made about the binary system. So for instance, the best estimate of the mass of the black hole in V404 Cygni is about $12M_\odot$. A summary of mass measurements of some other black hole candidates is given in Figure 9.22.

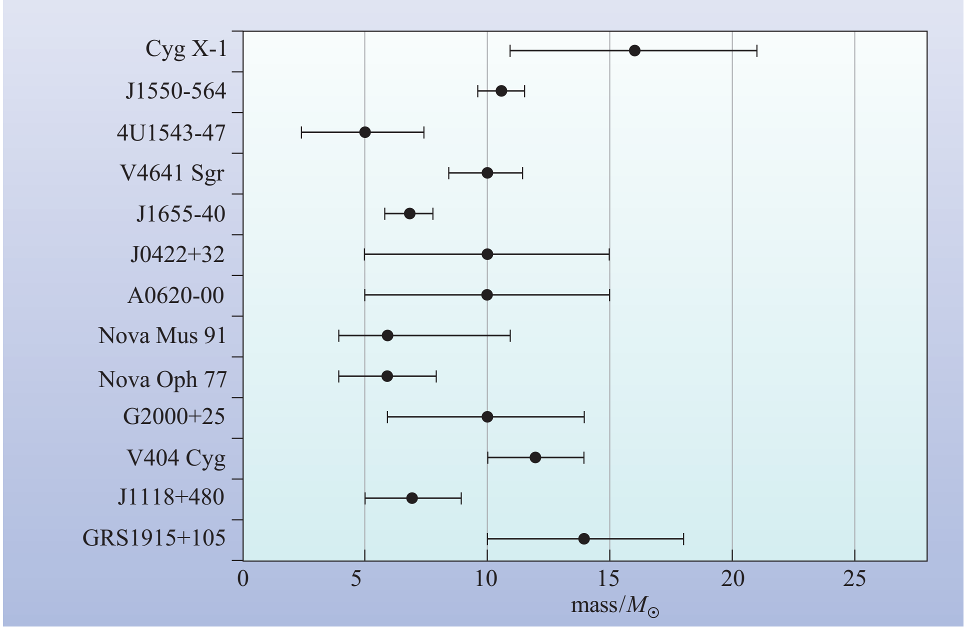


Figure 9.22 A summary of mass determinations, with uncertainties, of a selection of black hole candidates. (Data compiled by S. Clark (University College London))

It is thought that mass transfer in most black hole candidate systems occurs by Roche lobe overflow although there are a few cases in which stellar wind accretion seems a more likely mechanism. Since the black hole has no surface, any X-ray emission that is observed must originate from the accreting material that surrounds the black hole. The outburst behaviour of sources such as V404 Cygni is, in some respects, similar to the outburst behaviour of dwarf novae, and probably arises from an instability in the accretion disc. Although we have concentrated here on the differences between interacting binaries that contain white dwarfs, neutron stars or black holes, it is worthwhile bearing in mind that these systems have many features in common that result from the presence of an accretion disc, and that the process of accretion is in itself a topic of much research effort.

9.5.5 Interacting binaries – effects of binarity on evolution

How did interacting binaries get to their present form, and what will they become next? We assume that both stars were formed at the same time, but that they did not necessarily have the same mass.

- How does the mass of a star affect its rate of evolution?
- The more massive stars take a shorter time to go through their life cycle.

Suppose we have a binary system in which the more massive star has reached the red giant stage while the less massive star is still on the main sequence. As it expands, the envelope of the red giant is held less tightly by the giant's gravity. Meanwhile, part of the envelope is coming closer to the other star and more under the influence of its gravity. Eventually, the envelope may fill the Roche lobe and mass transfer will begin. As the giant star loses mass, its Roche lobe shrinks, but the star's radius changes very little; this enhances the mass transfer. The temperature and luminosity of the giant drop and those of the other star increase.

Following the evolution further, we find that the former giant (we shall call this star 1 from now on) can lose all its outer layers, possibly leaving a naked helium star. The second star is now the more massive and is a bright main sequence star. Nuclear reactions will cease in star 1 and it will become a white dwarf, or perhaps a neutron star. We shall then have a system with an old white dwarf and an *apparently* younger, more massive main sequence star. Figure 9.23 illustrates this sequence.

What happens next? The system remains in this configuration for quite some time, but eventually star 2 will reach the end of its main sequence lifetime; depending on how massive it is, there can be various outcomes. During its red giant or supergiant phase it may fill its Roche lobe and lose mass to star 1 (the white dwarf or neutron star). A number of known cataclysmic variables and X-ray binaries are at this stage of evolution.

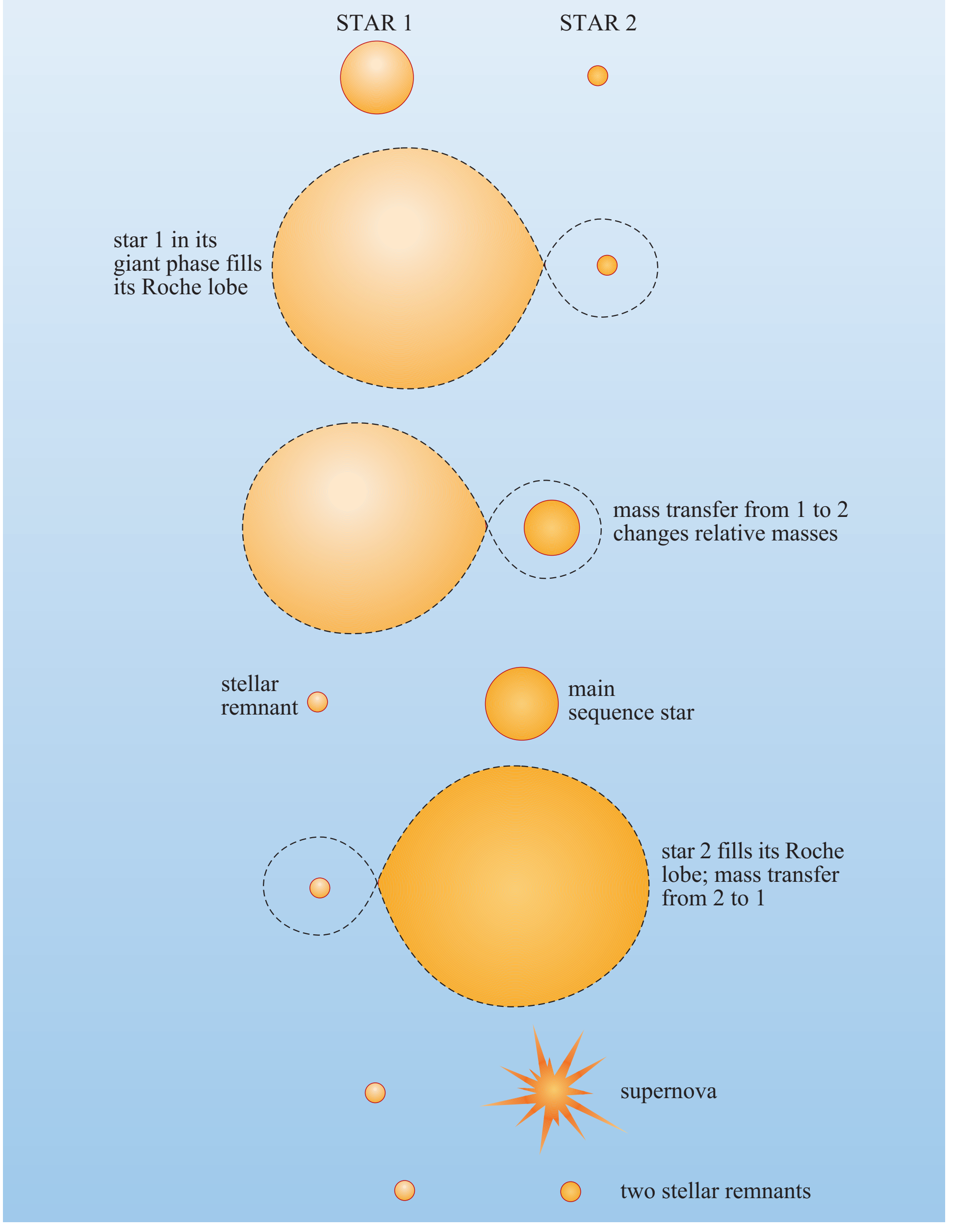


Figure 9.23 The evolution of an interacting binary system. Star 1 is initially the more massive.

If star 2 does not lose too much mass this way, then it may continue its evolution and become a supernova (or even a black hole) so that we can find binary systems that contain a white dwarf and a black hole. Note that there can be variants on this – the origins of many kinds of unusual system can be explained through the evolution of interacting binaries.

9.5.6 Supernovae in binaries

One of the most intriguing effects that is believed to arise in binary systems is a supernova mechanism that is quite distinct from that which is caused by the core collapse of an isolated high-mass star.

- ■ Which classes of supernova are believed to arise from the core collapse in a supergiant star?
- ❑ Type II, Ib and Ic supernovae are all believed to arise from core collapse in high-mass stars (Section 8.3.1).

As has already been noted in Section 8.3.1, Type Ia supernovae do not appear to be associated with sites of star formation and hence cannot arise from processes involving high-mass stars. A plausible model for these type of supernova explosions is one in which mass transfer occurs onto a white dwarf whose mass is close to the Chandrasekhar limit. In this scenario, the white dwarf is composed of carbon and oxygen.

- ■ Is it possible to obtain energy from nuclear fusion reactions involving carbon or oxygen?
- ❑ Yes – fusion reactions are exothermic for all elements with mass numbers lower than those around iron.

Because the material in the white dwarf has not reached the end point of nuclear burning, the Type Ia supernova process is quite different to core collapse in a massive star. As the white dwarf mass approaches the Chandrasekhar limit, the interior temperature increases to the point at which carbon starts to undergo fusion reactions. Once a region is heated by fusion reactions, neighbouring regions are heated by conduction or convection and these too can start to burn. The way in which the zones of nuclear burning propagate through the white dwarf is in many respects similar to the way in which a flame propagates in a chemical fire. Attempts to understand this process by using computer models are an area of active research, and are a challenge to the fastest available computers. An example of a computer model of the propagation of the nuclear 'flame' through a white dwarf is shown in Figure 9.24 (overleaf).

Given the complexity of this rapid thermonuclear burning, it is perhaps not surprising that numerical models are not yet able to predict the exact outcome of such events. Rather the approach taken is to see whether such models can reproduce some of the observed features of Type Ia supernovae. It seems that this type of model can produce an explosion of the correct magnitude and a distribution of elements up to and including the iron group that matches observation.

The successful models have the following features. In the central regions of the supernova, the temperatures reach about 10^{10} K and nuclear reactions proceed to the point where essentially all of the nuclei are converted into iron, cobalt or nickel. In regions further out from the core, temperatures are high enough to form nuclei such as silicon and calcium, but not nuclei of the iron group. The process is rapid, the white dwarf undergoes thermonuclear burning in a matter of seconds, and it is thought that as the zone of nuclear burning moves outwards it accelerates and becomes explosive. The explosion disperses the newly synthesized elements.

- A large mass of $^{56}_{27}\text{Co}$ is formed as a result of the Type Ia supernova explosion. By analogy with the light curve of Type II supernovae, what would you expect an observational consequence of this to be?

- Decay of $^{56}_{27}\text{Co}$ releases energy that emerges as visible light. It is likely that the visible light curve will decay in the same way that $^{56}_{27}\text{Co}$ decays.

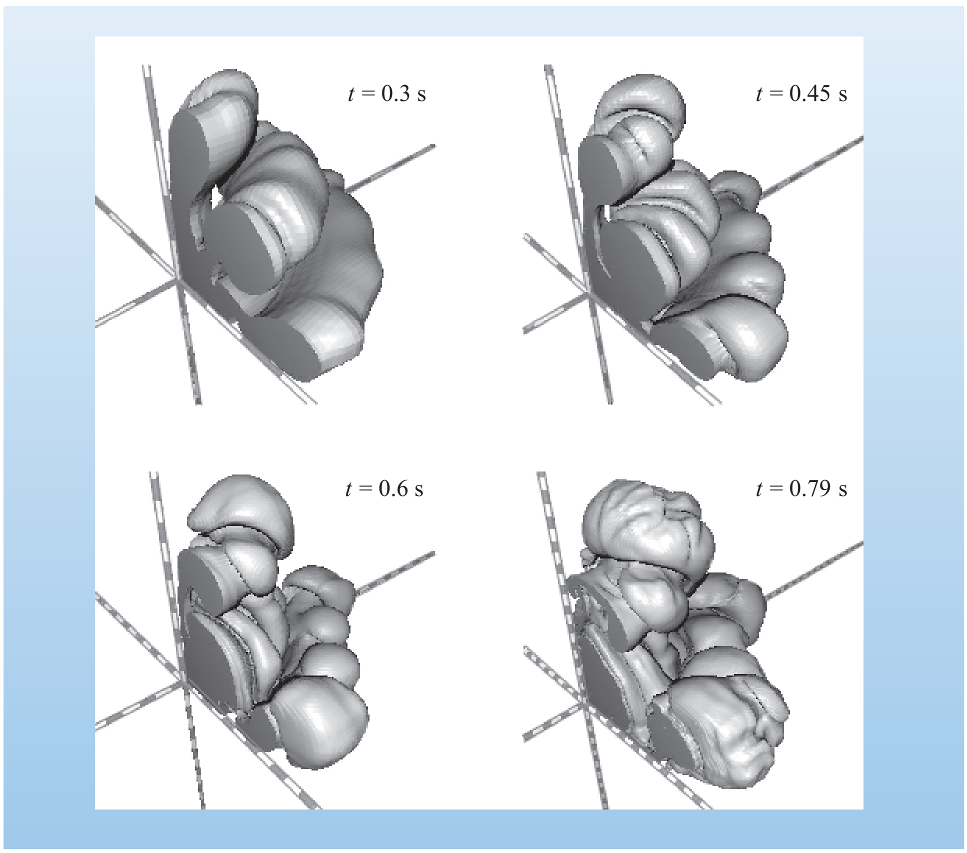


Figure 9.24 A computer simulation of the way in which nuclear burning propagates through a carbon–oxygen white dwarf that is at the Chandrasekhar limit. These plots show one-eighth of the volume of the white dwarf, with the centre of the star at the intersection of the axes. The surface represents the narrow zone in which thermonuclear burning is taking place. The sequence shows how this nuclear 'flame' evolves with time: the nuclear burning starts at the centre of the white dwarf at time $t = 0$ and the snapshots show how it progresses within one second. Note that the tick marks on the axes represent a length of 1×10^5 m and that the scale varies between the images. Thus, the surface of nuclear burning expands outwards through the white dwarf during the sequence. (Reinecke *et al*., 2002)

This is indeed what is found; the light curves of Type Ia supernovae seem to reflect the radioactive decay of ${}^{56}_{27}\mathrm{Co}$. The mass of radioactive elements formed in the explosion has been estimated as being about $0.6M_{\odot}$ in all such supernovae. The energy liberated as kinetic energy and electromagnetic radiation is similar to that released in a Type II supernova explosion.

QUESTION 9.13

Why are Type II and Type Ia supernovae *not* similar in terms of the *total* amount of energy released? What would you expect the total energy released in a Type Ia supernova to be in comparison to the total energy released in a Type II supernova?

A remarkable feature of supernovae of Type Ia is that the peak luminosity of all such explosions is believed to be constant to within about 15%. We have already seen in Chapter 3 (Section 3.3.3) that the distance to a star of known luminosity L can be determined by measuring its flux density F and using Equation 3.12

$$d = \sqrt{\frac{L}{4\pi F}}$$

The same technique can be applied to any source whose intrinsic luminosity is known. This approach to the determination of distance is called a 'standard candle' method, and it turns out that supernovae of Type Ia seem to provide the best standard candle for distances on cosmological scales (i.e. greater than 10^8 pc). Given the importance of Type Ia supernovae to cosmology, they are the subject of much observational and theoretical scrutiny.

Despite intensive research into the nature of Type Ia supernovae, there are some major issues that are yet to be resolved. Firstly, the nature of the mass-donating star in the binary is unknown. There is no case in which the progenitor of a Type Ia supernova has been observed, and given the low frequency of occurrence of supernovae and the probable low luminosity of a pre-supernova binary, it seems unlikely that we will observe such a system in the near future. In some models matter is assumed to be transferred from a main sequence or giant star onto the white dwarf. If this is the case, there is a puzzle as to why the spectrum of the supernova shows no trace of hydrogen or helium. One suggestion is that the transferred material might undergo steady nuclear burning on the surface of the white dwarf such that no significant quantities of hydrogen or helium accumulate. An alternative scenario is that the explosion is the result of the coalescence of two white dwarfs, which would naturally explain the absence of hydrogen features from the observed spectrum. The debate as to which of these models is more appropriate to Type Ia supernovae is on-going.

9.6 Summary of Chapter 9

White dwarfs

- White dwarfs are the remnants of stars which have an initial mass of less than $11M_\odot$.
- Such stars are formed from the cores of giant stars once nuclear burning has ceased. After depletion of all nuclear fuels, the core collapses until degeneracy pressure is able to prevent further collapse.
- With no further nuclear reactions possible, the white dwarf cools and disappears from view.
- White dwarfs cannot have a mass above the Chandrasekhar limit of $1.4M_\odot$.

Neutron stars

- Neutron degeneracy pressure allows the existence of another stable form of stellar matter, more dense than the white dwarf and rich in neutrons. This type of star is known as a neutron star.
- Such a star is formed when the core of a supergiant collapses in a supernova explosion.
- There is a maximum mass that a neutron star can have. This is certainly less than $5M_\odot$ and thought to be around $3M_\odot$. All neutron stars whose mass has been measured are lower than this limit.
- Angular momentum is conserved in the collapse of the core of the supergiant, and so the neutron star will be rotating very rapidly on its axis.
- Magnetic field lines are trapped as the core collapses and consequently the neutron star will have a very strong magnetic field.
- Pulsars are rapidly rotating, highly magnetized neutron stars, which produce beamed radio emission. As the star rotates, the beam is swept around the sky. If the orientation is such that the beam sweeps across the Earth, regular pulses of radio emission can be observed repeating at the pulsar rotation period.

Black holes

- A black hole is believed to be the end-point of the evolution of a star too massive to become a neutron star.
- The Schwarzschild radius of a black hole of mass M is given by

$$R_S = \frac{2GM}{c^2}$$

- When an object collapses to a radius smaller than its Schwarzschild radius then its collapse cannot be halted, and nothing can escape from it.

Interacting binary stars

- Roche lobe overflow and stellar wind accretion are processes that result in the transfer of material in a close binary system.
- When matter accretes onto a white dwarf, a neutron star or a black hole, gravitational potential energy is released, typically leading to emission in the X-ray band.
- The existence of pulsars in binary systems (both interacting and non-interacting) allows the masses of neutron stars to be measured.

- A black hole in a binary-star system may be detectable through the emission of X-rays from an accretion disc. The X-ray source V404 Cygni is almost certainly one such system. Estimates of the mass of the non-luminous star in a binary can help to confirm the existence of a black hole.
- If a star is one of a close binary system, its evolution will be significantly modified because of the transfer of material between the two stars in the system.
- Many unusual binary systems, such as those containing two compact objects, or a compact object and a more normal star, can be accounted for by the evolution of interacting binary systems.
- Supernovae of Type Ia are believed to occur in interacting binaries and arise from the complete nuclear burning of a white dwarf that is close to the Chandrasekhar limit. The nuclear burning results in the formation of a relatively large mass of iron group elements.

Questions

QUESTION 9.14

A malfunctioning satellite, of moment of inertia 2500 kg m^2, spinning at 0.33 revolutions per second, is to be repaired by a visiting astronaut. The satellite is cylindrical in shape with radius 1 m. The astronaut, who has a mass of 100 kg, latches on to the curved surface of the satellite. At how many revolutions per second will the satellite–astronaut combination rotate? (*Hint*: assume that the astronaut can be considered to be a point mass at a distance of 1 m from the axis of rotation.)

QUESTION 9.15

If the power received at the Earth from a pulsar is 10^{-19} W m^{-2} and you have a radio telescope of collecting area 1000 m^2, compare the power received by the telescope from the pulsar with the power you would use lifting this book (which weighs about 1 kg) through a height of 1 m in 1 second.

QUESTION 9.16

A supergiant, spectral class B, mass $15M_{\odot}$, is in a non-interacting binary system with a pulsar. The B star has emission lines; describe how the spectrum seen by an optical astronomer changes during one orbital period. What changes does a radio astronomer see during one orbital period? Outline the history and future evolution of the binary system.